Possibility of Studying Electroweak Symmetry Breaking at $\gamma\gamma$ Colliders

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ABSTRACT

The studies of the electroweak symmetry breaking sector (EWSBS) at $\gamma\gamma$ colliders were considered previously in the loop processes of $\gamma\gamma \to w_L w_L,\ z_L z_L$, but they are suffered from the huge $W_T W_T$ and $Z_T Z_T$ backgrounds. Here we present another possible process that involves spectator W's and W_L's, the latter of which are scattered strongly by the interactions of the EWSBS. We also show that this process should be safe from the transverse backgrounds and it can probe the structure of the EWSBS.

I. INTRODUCTION

So far very little is known about the electroweak symmetry-breaking-sector (EWSBS), except it gives masses to the vector bosons via the spontaneous symmetry breaking, and masses to fermions via the Yukawa couplings. In the minimal standard model (SM) one scalar Higgs boson is responsible for the electroweak symmetry breaking but its mass is not determined by the model. If in the future no Higgs boson is found below 800 GeV, the heavy Higgs scenario ($\approx$ 1 TeV) will imply a strongly interacting Higgs sector because the Higgs self-coupling $\lambda \sim m_H^2$ becomes strong [1]. However, there is no evidence to favor the model with a scalar Higgs, and so any models that can break the electroweak symmetry the same way as the single Higgs does can be a candidate for the EWSBS.

One of the best ways to uncover the underlying dynamics of the EWSBS is to study the longitudinal vector boson scattering [1,2]. The Equivalence Theorem (ET) recalls, at high energy, the equivalence between the longitudinal part (W_L) of the vector bosons to the corresponding Goldstone bosons (w_L) that were "eaten" in the Higgs mechanism. These Goldstone bosons originate from the EWSBS so that their scattering must be via the interactions of the EWSBS, and therefore the $W_L W_L$ scattering can reveal the dynamics of the EWSBS.

The strong $W_L W_L$ scattering have been studied quite seriously at the hadronic supercolliders [3], but less at the e^+e^- colliders, and very little at the $\gamma\gamma$ colliders. In hadronic colliders, only the "gold-plated" modes, the leptonic decays of the W and Z bosons, have been considered due to the messy hadronic backgrounds; whereas in e^+e^- and $\gamma\gamma$ colliders one can make use of the hadronic decay mode or mixed decay mode of the final state W's or Z's. With the advance in the photon collider designs it is possible to construct an almost monochromatic $\gamma\gamma$ collider based on the next generation linear e^+e^- colliders using the laser backscattering method [4]. The monochromaticity of the photon beams depends on the polarizations of the initial electron and the laser photon. The polarizations of the initial electron and the laser photon can be adjusted to maximize the monochromaticity of

the photon beam [4] with a center-of-mass energy about 0.8 of the parent e^+e^- collider. Hence, a 2 TeV e^+e^- collider will give a 1.6 TeV $\gamma\gamma$ collider by the laser backscattering method. For the following we will assume a monochromatic $\gamma\gamma$ collider of energy 1.5 TeV with an integrated luminosity of 100 fb^{-1}.

Studies of the strongly interacting EWSBS in $\gamma\gamma$ collision have been considered previously in Refs. [5]. They all concentrate on $\gamma\gamma \to W_L W_L$ or $Z_L Z_L$. Unfortunately, the $\gamma\gamma \to W_T W_T$ is almost three orders of magnitude larger than the $W_L W_L$ signal. Although we can improve the signal-to-background ratio by requiring the final state W's away from the beam, it hardly reduces the $W_T W_T$ background to the level of the $W_L W_L$ signal. On the other hand, both the $\gamma\gamma \to ZZ$ signal and background are absent on tree level. But the box diagram contribution to $Z_T Z_T$ has been shown to be very large at high $m(ZZ)$ region, and so the $Z_T Z_T$ background is dominant over the $Z_L Z_L$ signal in the search of the SM Higgs with $m_H \gtrsim 300$ GeV and in probing the other strong EWSB signals [6]. As illustrated in Refs. [5], the central part of interest is the $w_L w_L \to w_L w_L$ or $z_L z_L$, but the effects of the strong EWSBS only come in on loop level in these processes so that the effects might not be so significant.

In the following we present a new type of processes involving $W_L W_L \to W_L W_L$, $Z_L Z_L$ at $\gamma\gamma$ colliders, schematically shown in Fig. 1 [7]. These $W_L W_L$ scattering processes will be in analogy to the $W_L W_L$ scattering considered at the hadronic supercolliders and e^+e^- colliders. The advantages of the processes in Fig. 1 are that the $W_L W_L$ scattering is no longer on loop level, and additional vector bosons in the final state can be tagged on to eliminate the large $W_T W_T$ and $Z_T Z_T$ backgrounds. In addition, both the $W_L^+ W_L^-$ and $W_L^\pm W_L^\pm$ scattering can be studied in $\gamma\gamma$ collision but only one of them can be studied in the e^+e^- or e^-e^- collisions. Also any $Z_L Z_L$ pair in the final state must come from the $W_L W_L$ fusion because photon will not couple to Z on tree level. Totally, we can study four scattering processes, $W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$, $W_L^+ W_L^- \to W_L^+ W_L^-$, $Z_L Z_L$.

For simplification we will use the effective W_L luminosity inside a photon in analogy to the effective W approximation. This approximation will suffice for the purpose here for we will consider the kinematic region where the EWSBS will interact strongly, or in another

words, in the large invariant mass region of the vector boson pair. The luminosity function of a W_L inside a photon in the asymtotic energy limit is given by [8]

$$f_{W_L/\gamma}(x) = \frac{\alpha}{\pi}\left[\frac{1-x}{x} + \frac{x(1-x)}{2}\left(\log\frac{s(1-x)^2}{m_W^2} - 2\right)\right],\tag{1}$$

which is in analogy to the luminosity function $f_{W_L/e}(x) = \frac{\alpha}{4\pi x_{\mathrm{w}}}\frac{1-x}{x}$ of W_L inside an electron. The first term in Eq. (1) is approximately equal to the luminosity of W_L inside an electron, and the logarithm factor will enhance the luminosity at high energy. This is the reason why the signal rates can be achieved higher than those in the e^+e^- colliders at the same energy.

II. MODELS & PREDICTIONS

In this section, we will calculate the number of signal events predicted by some of the models that have been proposed for the EWSBS. In $\gamma\gamma$ collision we can study the following subprocesses

$$W_L^+ W_L^- \to W_L^+ W_L^- , Z_L Z_L ,\tag{2}$$

$$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm .\tag{3}$$

In analogy to the pion scattering in QCD, the scattering amplitudes of these processes can be expressed in terms of an amplitude function $A(s,t,u)$. Their scattering amplitudes are then expressed as

$$\mathcal{M}(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm) = A(t,s,u) + A(u,t,s)\,,\tag{4}$$

$$\mathcal{M}(W_L^+ W_L^- \to W_L^+ W_L^-) = A(s,t,u) + A(t,s,u)\,,\tag{5}$$

$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) = A(s,t,u)\,,\tag{6}$$

up to the symmetry factor of identical particles in the final state. The details of each model and the invariant amplitudes predicted by each model are summarized in Ref. [3]. Here we only give a brief account of these models. The models can be classified according to the spin and isospin of the resonance fields, and there are scalar-like, vector-like, and nonresonant

models. For scalar-like models we will employ the standard model with a 1 TeV Higgs, $O(2N)$ model with the cutoff $\Lambda = 2$ TeV, and the model with a chirally-coupled scalar of mass $m_S = 1$ TeV and width $\Gamma_S = 350$ GeV. For the vector-like models we choose the chirally-coupled vector field (technirho) of masses $m_\rho = 1$, 1.2, and 1.5 TeV, and $\Gamma_\rho = 0.4$, 0.5, and 0.6 TeV respectively. In the case of no light resonances we use the amplitudes predicted by the Low Energy Theorem (LET) and extrapolate them to high energies.

Each of the $W_L W_L$ scattering amplitudes grows with energy until reaching the resonances, *e.g.* SM Higgs boson of the minimal SM. The presence of the resonances (scalar or vector) is the natural unitarization to the scattering amplitudes, except there might be slight violation of unitarity around the resonance peak. After the resonance, the scattering amplitudes will stay below the unitarity limit. But for the nonresonant models the unitarity is likely to be saturated before reaching the lightest resonance. Here we employ the LET amplitude function, $A(s,t,u) = s/v^2$, for the nonresonant models. From the partial wave analysis, the only nonzero partial wave coefficients a_J^I are a_0^0, a_1^1, and a_0^2. Among the nonzero a_J^I's, a_0^0 saturates the unitarity ($|a_J^I| < 1$) at the lowest energy $4\sqrt{\pi}v \approx 1.7$ TeV. So for the $\gamma\gamma$ colliders of 1.5 TeV, unitarity violation should not be a problem, therefore, we simply extrapolate the LET amplitudes without any unitarization.

We show the number of signal events predicted by these models for each scattering channel in Table I, with $\sqrt{s_{\gamma\gamma}} = 1.5$ TeV and integrated luminosity of 100 fb^{-1}, and under the acceptance cuts of

$$M_{WW} \text{ or } M_{ZZ} > 500\,\text{GeV} \quad \text{and} \quad |y(W,Z)| < 1.5 \,. \tag{7}$$

One interesting thing to note here is that different channel is sensitive to different new physics. If the underlying dynamics of the EWSBS is scalar-like the signal is more likely to be found in the $W_L^+ W_L^-$ channel, and next at the $Z_L Z_L$ channel, due to the presence of $I = 0, J = 0$ scalars. But if the underlying dynamics is vector-like the signal in the $W_L^+ W_L^-$ channel will be far more important that the $Z_L Z_L$ channel. On the other hand, if no light resonances are within reach the $Z_L Z_L$ channel has the largest signal rate, and next is the

$W_L^\pm W_L^\pm$ channels. So by counting the number of $W_L^\pm W_L^\pm$, $W_L^+ W_L^-$, and $Z_L Z_L$ pairs in the final state one can tell the different structure of the EWSBS [9]. But to distinguish a W from a Z by the dijet mass measurement is not a trivial issue, though we can use the B-tagging to distinguish a W from a Z somehow. For a discussion on this subject please see, *e.g.*, Ref. [9].

The number of signal events in Table I does not include any detection efficiencies of the W_L's coming out from the strong scattering region, nor the tagging efficiencies for the spectator W's. The tagging efficiencies for the spectator W's will be dealt with in the next section. The detection efficiencies of the W_L's consist of the branching ratios of the W_L into jets or leptons, and the tagging efficiencies of these decay products. The branching ratio $\mathrm{BR}(W \to jj) \approx \mathrm{BR}(Z \to jj) \approx 0.7$. Assuming a 30% (reasonable to pessimistic) tagging efficiencies for the decay products, we have about 15% overall detection efficiencies for the $W_L W_L$ coming out from the strong scattering region.

III. TAGGING THE SPECTATOR W'S

So far we have not considered any backgrounds nor background suppression techniques. In our calculation, we use the effective W_L luminosity which does not predict the correct kinematics for the spectator W's, and therefore any acceptance cuts on the spectator W's will be unrealistic. However, we need to tag at least one or both of these spectator W's in order to eliminate the enormous $\gamma\gamma \to W_T W_T$, $Z_T Z_T$ backgrounds. One way to remedy is to carry out an exact SM calculation of $\gamma\gamma \to WWWW$ or $WWZZ$ with a heavy Higgs boson, and estimate the acceptance efficiencies on tagging the spectator W's, and then apply these efficiencies to the other models which can only be calculated using the effective W_L luminosity.

However, the calculations of the processes $\gamma\gamma \to WWWW$ or $WWZZ$ are non-trivial. Instead, we can obtain the tagging efficiencies by calculating a simpler process $\gamma\gamma \to WWH$ for $m_H \approx 1$ TeV, with and without imposing acceptance cuts on the final state W's. We

will calculate the total cross section for $\gamma\gamma \to WWH$ without any cuts, and also the cross section with the acceptance cuts

$$p_T(W) > 25 \text{ GeV}, \qquad |y(W)| < 1.5 \text{ or } 2 \tag{8}$$

on either one or both of the W's. The cross sections are presented in Table II for $m_H = 1$ TeV. There are two tagging efficiencies corresponding to tagging at least one or both of the spectator W's. From Table II, if we require the spectator W's within a rapidity of $|y(W)| < 1.5$ the tagging efficiencies are 91% and 42% for tagging at least one or both the W's respectively. To eliminate the $W_T W_T$ or $Z_T Z_T$ backgrounds we need only tag one of the spectator W's plus the W_L's from the strong scattering. A further confirmation by tagging two spectator W's will result in an efficiency of only 42%. But if we tag both spectator W's within the rapidity $|y(W)| < 2$ the double-tag efficiency increases to 82%. This drastic difference of the double-tag efficiencies between rapidity cut of 1.5 and 2 demonstrates that it is likely (40% chance) to have at least one spectator W in the forward rapidity region $1.5 < |y(W)| < 2$. Next we can multiply these efficiencies to the numbers in Table I to get a more reliable number of signal events when the spectator W's are tagged. Taking into account of the 15% (from the last section) detection efficiency for the $W_L W_L$ plus the tagging efficiency of at least one or both of the spectator W's, we still have at least 10% overall efficiency. With 10% efficiency we still have a sizeable number of signal events. Scalar-type models will be shown up in the $W^+ W^- \to W^+ W^-$ channel with at least 47 events. The vector-like models will also be shown up in the $W^+ W^- \to W^+ W^-$ channel if the vector resonance is within reach of the energy of the $\gamma\gamma$ collider. For nonresonant models we have about 15 events for the $W^\pm W^\pm \to W^\pm W^\pm$ channels and 17 events for $W^+ W^- \to ZZ$ channel.

IV. BACKGROUND DISCUSSIONS

The continuum productions of $\gamma\gamma \to WWWW$ and $WWZZ$, together with the heavy quark production of $\gamma\gamma \to t\bar{t}t\bar{t}$ followed by the top decays into W's, form the irreducible

set of backgrounds. They are the SM predictions that any significant excess of $W_L W_L$ or $Z_L Z_L$ events will indicate some kinds of new physics for the EWSBS. The other reducible backgrounds include the productions of W's with jets, Z's with jets, and multi-jet.

The $WWWW$ and $WWZZ$ productions are of order α_w^4, and so should be at most the same level as our strong $W_L W_L$ signal. Although the $t\bar{t}t\bar{t}$ background is $\mathcal{O}(\alpha_s^2/\alpha_w^2)$ larger than the $WWWW$ background, we can to certain extent reduce it by reconstructing the top and by imposing the top-mass constraints. The other QCD backgrounds of W's or Z's with jets are reducible by the W or Z mass constraints.

In addition, we can make use of the kinematics of the spectator W's and the strongly scattered W_L's [10]. The p_T of the spectator W's should be of order $m_W/2$ after the photon emits an almost on-shell W_L, which then participates in the strong scattering. Also, as mentioned in the last section, at least one of the spectator W's tend to go forward in the rapidity region $|y(W)| > 1.5$. On the other hand, the $W_L W_L$ after the strong scattering come out in the central rapidity region with large p_T and large invariant mass, and back-to-back in the transverse plane, which are all due to the strong interaction of the EWSBS. But it is hardly true for the backgrounds. Acceptance cuts can be formulated based on the above arguments to substantially reduce the backgrounds [11].

In conclusions, we have demonstrated another type of processes in $\gamma\gamma$ collision that can probe the strongly interacting EWSBS scenario. The processes do not involve the indirect loop effects, and also are safe from the huge $W_T W_T$ or $Z_T Z_T$ backgrounds due to the presence of the spectator W's. Even with only 10% overall efficiency we still have enough signal events with 100 fb^{-1} luminosities. Irreducible backgrounds from $WWWW$, $WWZZ$, and $t\bar{t}t\bar{t}$ can be reduced by considering the special kinematics of the strongly scattered W_L's and the spectator W's. Other reducible backgrounds are reduced by the mass constraints.

ACKNOWLEDGMENTS

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[11] K.Cheung, in preparation.

TABLES

TABLE I.   The number of the signal events for the strong $W_L W_L$ scattering predicted by various models at $\gamma\gamma$ collider of $\sqrt{s} = 1.5$ TeV. The acceptance cuts on the final $W_L W_L$ or $Z_L Z_L$ are: $m(WW, ZZ) > 500$ GeV and $|y(W, Z)| < 1.5$. The luminosity is assumed 100 fb^{-1}. No efficiencies are included here.

	$W_L^+ W_L^+ \to W_L^+ W_L^+$	$W_L^+ W_L^- \to W_L^+ W_L^-$	$W_L^+ W_L^- \to Z_L Z_L$
(1) SM Higgs			
$m_H = 1$ TeV	88	1600	760
(2) chirally-coupled scalar			
$m_S = 1$ TeV, $\Gamma_S = 350$ GeV	100	570	430
(3) O(2N)	90	470	350
(4) chirally-coupled vector			
a. $m_V = 1$ TeV, $\Gamma_V = 0.4$ TeV	180	2400	280
b. $m_V = 1.2$ TeV, $\Gamma_V = 0.5$ TeV	52	590	29
c. $m_V = 1.5$ TeV, $\Gamma_V = 0.6$ TeV	88	120	40
LET	150	110	170

TABLE II. Table showing the cross sections (fb) for the process $\gamma\gamma \to WWH$ with a SM Higgs boson of mass $m_H = 1$ TeV at $\sqrt{s_{\gamma\gamma}} = 1.5$ TeV, with and without imposing acceptance cuts on the final state W's. The acceptance cuts are $p_T(W) > 25$ GeV and $|y(W)| < 1.5$ or 2. The second column shows the total cross section without cuts. The third column corresponds to tagging at least one of the W's, and the last column corresponds to tagging both. The percentages in the parentheses are the efficiencies.

$|y(W)| <$	No cuts	Tagging at least one W	Tagging both W's
-	14.7	-	-
1.5	-	13.4 (91%)	6.16 (42%)
2.0	-	14.5 (98.5%)	12.1 (82%)

FIGURES

FIG. 1.   Schematic diagram for the $W_L W_L$ scattering in $\gamma\gamma$ collision.

This figure "fig1-1.png" is available in "png" format from:

http://arXiv.org/ps/hep-ph/9310340v1